Robotics and Automation

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Although shuttle astronauts made their work in space look like an everyday event, it was in fact a hazardous operation. Using robotics or human-assisted robotics and automation eliminated the risk to the crew while still performing the tasks needed to meet the mission objectives. The Shuttle Robotic Arm, commonly referred to as "the arm," was designed for functions that were better performed by a robotic system in space.

Automation also played an important role in ground processing, inspection and checkout, cost reduction, and hazardous operations. For each launch, an enormous amount of data from verification testing, monitoring, and command procedures were compiled and processed, often simultaneously. These procedures could not be done manually, so ground automation systems were used to achieve accurate and precise results. Automated real-time communication systems between the pad and the vehicle also played a critical role during launch attempts. In addition, to protect employees, automated systems were used to load hazardous commodities, such as fuel, during tanking procedures. Throughout the Space Shuttle Program, NASA led the development and use of the most impressive innovations in robotics and automation.

Shuttle Robotic Arm—Now That You Have the "TRUCK," How Do You Make the Delivery?

Early in the development of the Space Shuttle, it became clear that NASA needed a method of deploying and retrieving cargo from the shuttle payload bay. Preliminary studies indicated the need for some type of robotic arm to provide both capabilities. This prompted the inclusion of a Shuttle Robotic Arm that could handle payloads of up to 29,478 kg (65,000 pounds).

In December 1969, Dr. Thomas Paine, then administrator of NASA, visited Canada and extended an offer for Canadian participation with a focus on the Space Shuttle. This was a result of interest by NASA and the US government in foreign participation in post-Apollo human space programs. In 1972, the Canadian government indicated interest in developing the Shuttle Robotic Arm. In 1975, Canada entered into an agreement with the US government in which Canada would build the robotic arm that would be operated by NASA.

The Shuttle Robotic Arm was a three-joint, six-degrees-of-freedom, two-segment manipulator arm to be operated only in the microgravity environment. From a technical perspective, it combined teleoperator technology and composite material technology to produce a lightweight system useable for space applications. In fact, the arm could not support its own weight on Earth. The need for a means of grappling the payload for deployment and retrieval became apparent. This led to an end effector—a unique electromechanical device made to capture payloads.

Unique development and challenges of hardware, software, and extensive modeling and analysis went into the Shuttle Robotic Arm's use as a tool for delivery and return of payloads to and from orbit. Its role continued in the deployment and repair of the Hubble

Backdropped by the blackness of space and Earth's horizon, Atlantis' Orbiter Docking System (foreground) and the Canadarm—the Shuttle Robotic Arm developed by Canada—in the payload bay are featured in this image photographed by an STS-122 (2008) crew member during Flight Day 2 activities.

Space Telescope, its use in the building of the space station and, finally, in Return to Flight as an inspection and repair tool for the Orbiter Thermal Protection System.

Evolution of the Shuttle Robotic Arm

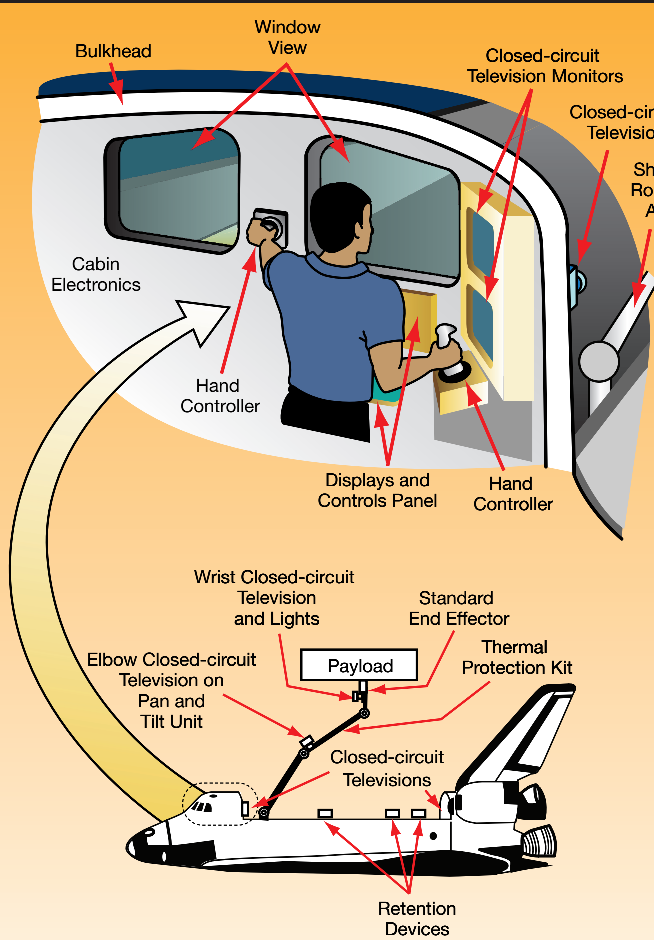
The initial job of the Shuttle Robotic Arm was to deploy and retrieve payloads to and from space. To accomplish this mission, the system that was developed consisted of an anthropomorphic manipulator arm located in the shuttle cargo bay, cabin equipment to provide an interface to the main shuttle computer, and a human interface to allow an astronaut to control arm operations remotely.

The manipulator arm consisted of three joints, two arm booms, an end effector, a Thermal Protection System, and a closed-circuit television system. Arm joints included a shoulder joint with two degrees of freedom (yaw and pitch), an elbow joint with one degree of freedom (pitch), and a wrist joint with three degrees of freedom (pitch, yaw, and roll). Each joint degree of freedom consisted of a motor module driving a gear box to effect joint movement and appropriate local processing to interpret drive commands originating from the cabin electronics.

The cabin electronics consisted of a displays and controls subsystem that provided the human-machine interface to allow a crew member to command the arm and display appropriate information, including arm position and velocity, end effector status, temperature, and caution and warning information. Additionally, in the displays and controls subsystem, two hand controllers allowed man-in-the-loop control of the end point of the arm. The main robotic arm processor—also part of the cabin electronics—handled all data transfer among the arm, the displays and controls panel, and the main shuttle computer. The main shuttle computer processed commands from the operator via the displays and controls panel; received arm data to determine real-time position, orientation, and velocity; and then generated rate and current limit commands that were sent to the arm-based electronics.

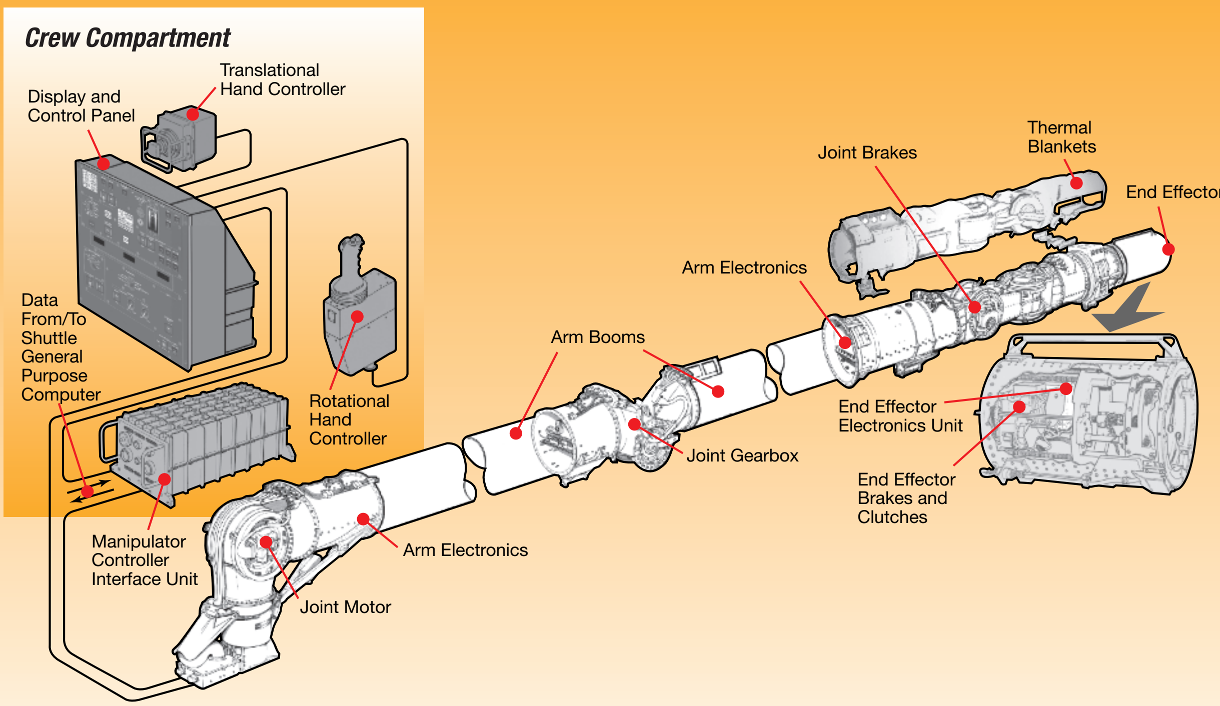
The arm was thermally protected with specially designed blankets to reduce the susceptibility of the hardware to thermal extremes experienced during spaceflight and had an active thermostatically controlled and redundant heater system.

Shuttle Robotic Arm System



A crew member could manually control the arm from inside the crew compartment using a translational hand controller and a rotational hand controller. The crew received feedback visually via the displays and controls panel and the closed-circuit television monitors, and directly through the shuttle crew compartment windows. The crew could also control the arm in automatic mode.

Components of the Shuttle Robotic Arm



With a total length of 15.24 m (50 ft), the Shuttle Robotic Arm consisted of two lightweight high-strength tubes, each 0.381 m (1.25 ft) in diameter and 6.71 m (22 ft) in length, with an elbow joint between them. From a shoulder joint at the base of the arm providing yaw and pitch movement, the upper boom extended outward to the elbow joint providing pitch movement from which the lower arm boom stretched to a wrist joint providing pitch, yaw, and roll movement. The end effector was used to grapple the payload.

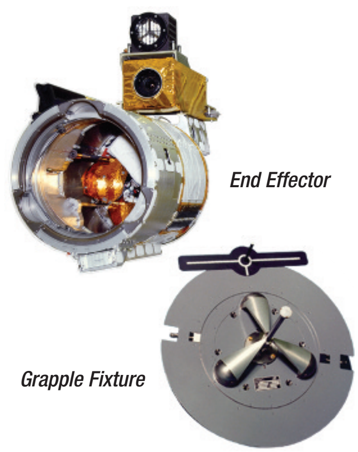
The closed-circuit television system consisted of a color camera on a pan/tilt unit near the elbow joint and a second camera in a fixed location on the wrist joint, which was primarily used to view a grapple fixture target when the arm was capturing a payload.

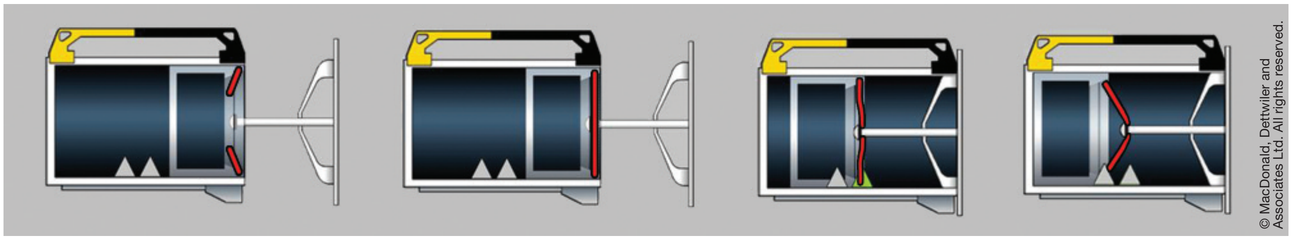
Self checks existed throughout all the Shuttle Robotic Arm electronics to assess arm performance and apply appropriate commands to stop the arm, should a failure occur. Caution and warning displays provided the operator with insight into the cause of the failure and remaining capability to facilitate the development of a workaround plan.

The interfacing end of the Shuttle Robotic Arm was equipped with a fairly complicated electromechanical construction referred to as the end effector. This device, the analog to a human hand, was used to grab, or grapple, a payload by means of a tailored interface known as a grapple fixture.

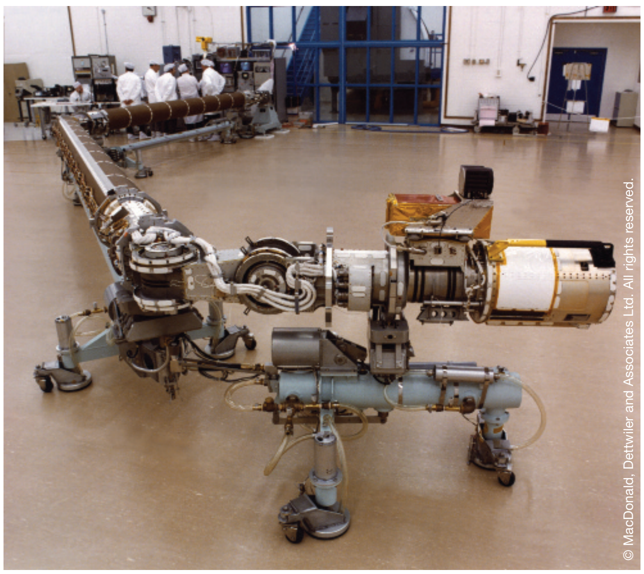
The end effector was equipped with a camera and light used to view the grapple fixture target on the payload being captured. The robotic arm provided video to the crew at the aft flight deck, and the camera view helped the crew properly position the end

Close-up View of End Effector and Grapple Fixture





End Effector Capture/Rigidize Sequence: The left frame illustrates the snares in the open configuration, and the second frame shows the snares closed around the grapple shaft and under the grapple cam at the tip of the grapple shaft. The next frame illustrates the snares pulling the grapple shaft inside the end effector so the three lobes are nested into the mating slots in the end effector, and the final frame shows the snare cables being pulled taut to ensure a snug interface that could transfer all of the loads.



Flat floor testing of the Shuttle Robotic Arm.

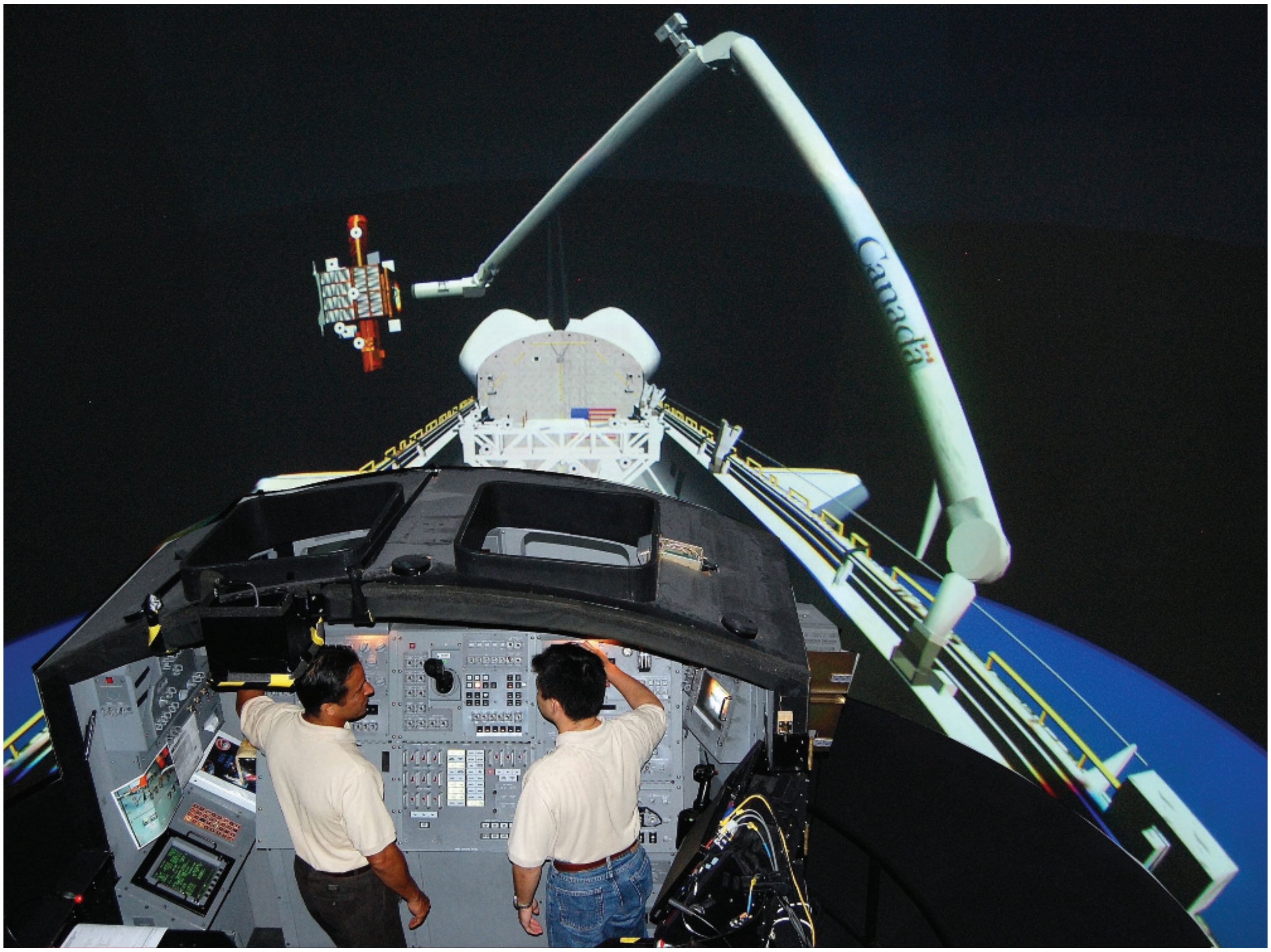
Challenger's (STS-8 [1983]) payload flight test article is lifted from the payload bay and held over clouds and water on Earth.

effector relative to the grapple fixture prior to capturing a payload. When satisfied with the relative position of the end effector to the payload grapple fixture using the grapple fixture target, the crew executed a command to capture and secure the payload.

Since the Shuttle Robotic Arm could not lift its own weight on Earth, all proposed operations had to be tested with simulations. In fact, terrestrial certification was a significant engineering challenge. Developing the complex equations describing the six-degrees-of-freedom arm was one technical challenge, but solving equations combining 0.2268-kg (0.5-pound) motor shafts and 29,478-kg (65,000-pound) payloads also challenged computers at the time. Canada—the provider of the Shuttle Robotic Arm—and the United States both developed simulation models. The simulation responses were tested against each other as well as data from component tests (e.g., motors, gearboxes) and flat floor tests. Final verification could be completed only on orbit. During four early shuttle flights, strain gauges were added to the Shuttle Robotic Arm to measure loads during test operations that started with an unloaded arm and then tested the arm handling progressively heavier payloads up to one emulating the inertia of a 7,256-kg (16,000-pound) payload—the payload flight test article. These data were used to verify the Shuttle Robotic Arm models.

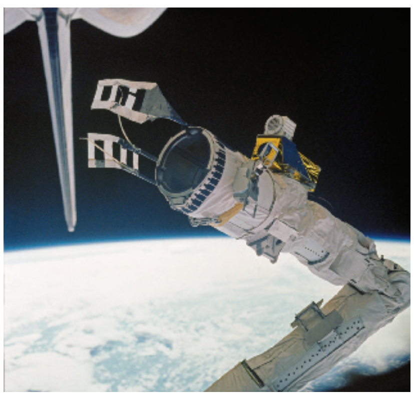
Future on-orbit operations were tested preflight in ground-based simulations both with and without an operator controlling the Shuttle Robotic Arm. Simulations with an operator in the loop used mock-ups of the shuttle cockpit and required calculation of arm response between the time the operator commanded arm motion with hand controllers or computer display entries and the time the arm would respond to commands on orbit. This was a significant challenge to then-current computers and required careful simplification of the arm dynamics equations. During the late 1970s and early 1980s, this necessitated banks of computers to process dynamic equations and specialized computers to generate the scenes. The first electronic scene generator was developed for simulations of shuttle operations, and payload handling simulations drove improvements to this technology until it became attractive to other industries. Simulations that did not require an operator in the loop were performed with higher complexity equations. This allowed computation of loads within the Shuttle Robotic Arm and detailed evaluation of performance of components such as motors.

Since the Shuttle Robotic Arm's job was to deploy and retrieve payloads to and from space, NASA determined two cameras on the elbow and wrist would be invaluable for mission support viewing since the arm could be maneuvered to many places the fixed payload bay cameras could not capture. As missions and additional hardware developed, unique uses of the arm emerged. These included "cherry picking" in space using a mobile foot restraint that allowed a member of the crew to have a movable platform from which tasks could be accomplished; "ice busting" to remove a large icicle that formed on the shuttle's waste nozzle; and "fly swatting" to engage a switch lever on a satellite that had been incorrectly positioned.

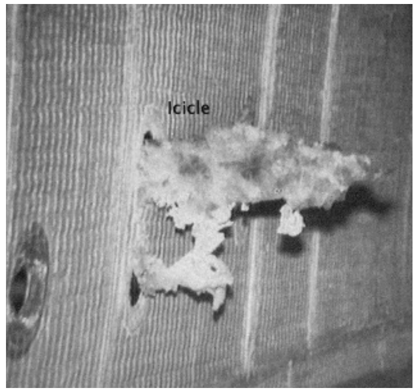


Astronauts Joseph Acaba and Akihiko Hoshide in the functional shuttle aft cockpit in the Systems Engineering Simulator showing views seen out of the windows. The Systems Engineering Simulator is located at NASA Johnson Space Center, Houston, Texas.

Cherry picking—On STS-41B (1984), Astronaut Bruce McCandless tests a mobile foot restraint attached to the Shuttle Robotic Arm. This device, which allowed a crew member to have a movable platform in space from which tasks could be accomplished, was used by shuttle crews throughout the program.



Fly swatting—On STS-51D (1985), the spacecraft sequencer on the Leasat-3 satellite failed to initiate antenna deployment, spin-up, and ignition of the perigee kick motor. The mission was extended 2 days to make the proper adjustments. Astronauts David Griggs and Jeffrey Hoffman performed a spacewalk to attach "fly swatter" devices to the robotic arm. Rhea Seddon engaged the satellite's lever using the arm and the attached "fly swatter" devices.



Ice busting—On STS-41D (1984), a large icicle formed on the shuttle's waste nozzle. NASA decided that the icicle needed to be removed prior to re-entry into Earth's atmosphere. The Shuttle Robotic Arm, controlled by Commander Henry Hartsfield, removed the icicle.

The Hubble Missions

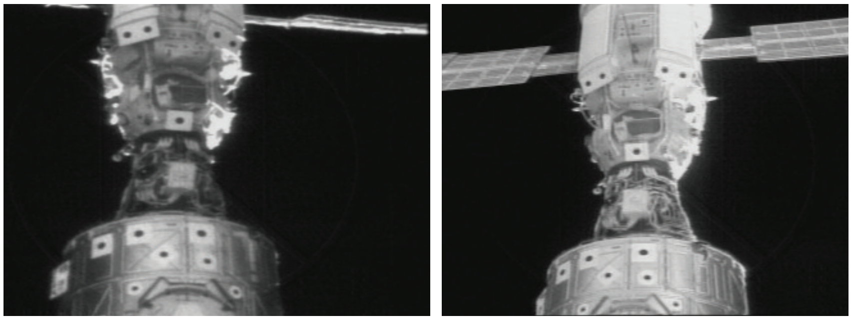
The Hubble Space Telescope, deployed on Space Transportation System (STS)-31 (1990), gave the world a new perspective on our understanding of the cosmos. An initial problem with the telescope led to the first servicing mission and the desire to keep studying the cosmos. The replacement and enhancement of the instrumentation led to a number of other servicing missions: STS-61 (1993), STS-82 (1997), STS-103 (1999), STS-109 (2002), and STS-125 (2009). From a Shuttle Robotic Arm perspective, the Hubble servicing missions showcased the system's ability to capture, berth, and release a relatively large payload as well as support numerous spacewalks to complete repair and refurbishment activities.

In the case of Hubble, the crew captured and mated the telescope to a berthing mechanism mounted in the payload bay to facilitate the repair and refurbishment activities. In this scenario, a keel target mounted to the bottom of Hubble was viewed with a keel camera and the crew used the Shuttle Robotic Arm to position the Hubble properly relative to its berthing interface to capture and latch it.

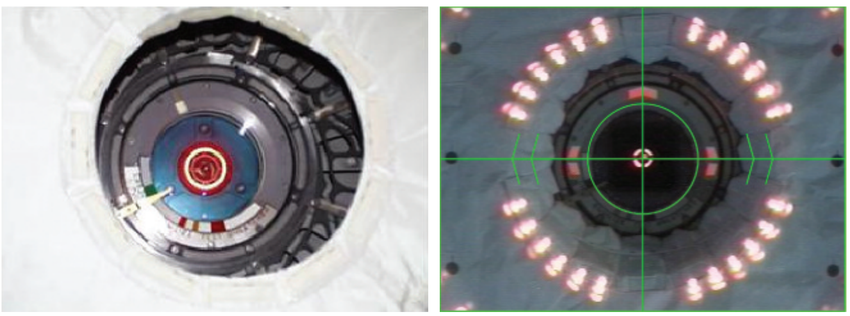
The Era of Space Station Construction

With STS-88 (1998)—the attachment of the Russian Zarya module to the space station node—the attention of the shuttle and, therefore, the Shuttle Robotic Arm was directed to the construction of the space station. Early space station flights can be divided broadly into two categories: logistics flights and construction flights. With the advent of the three Italian-built Multi-Purpose Logistic Modules, the Shuttle Robotic Arm was needed to berth the modules to the station. The construction flights meant attaching a new piece of hardware to the existing station. Berthings were used to install new elements: the nodes; the modules, such as the US Laboratory Module and the Space Station Airlock; the truss segments, many of which contained solar panels for power to the station; and the Space Station Robotic Arm. These activities required some modifications to the Shuttle Robotic Arm as well as the addition of systems to enhance alignment and berthing operations.

During preliminary planning, studies evaluated the adequacy of the Shuttle Robotic Arm to handle the anticipated payload operations envisioned for the space station construction. These studies determined that arm controllability would not be satisfactory for the massive payloads the arm would need to manipulate.



A robotic vision system known as the Space Vision System was used for the first space station assembly flight (STS-88 [1988]) that attached Node 1 to the Russian module Zarya. This Space Vision System used a robotic vision algorithm to interpret relative positions of target arrays on each module to calculate the relative position between the two berthing interfaces. The crew used these data to enhance placement to ensure a proper berthing. The two panes above show the camera views from the shuttle payload bay that the robotic vision system analyzed to provide a relative pose to the crew.



Centerline Berthing Camera System: A Centerline Berthing Camera System was later adopted to facilitate ease of use and to enhance the ability of the crew to determine relative placement between payload elements. The left pane shows the centerline berthing camera mounted in a hatch window with its light-emitting diodes illuminated. The right pane shows the display the crew used to determine relative placement of the payload to the berthing interface. The outer ring of light-emitting diode reflections come from the window pane that the camera was mounted against. However, these reflections never moved and were ignored. The small ring at the center of the crosshairs is the reflection of the Centerline Berthing Camera System light-emitting diodes in the approaching payload window being maneuvered by the Shuttle Robotic Arm system. This was used to determine the angular misalignment (pitch and yaw) of the payload. The red chevrons to the left and right were used to determine vertical misalignment and roll while the top red chevron was used to determine horizontal misalignment. The green chevrons in the overlay were used to determine the range of the payload. This system was first used during STS-98 (2001) to berth the US Laboratory Module (Destiny) to Node 1.

Redesigning the arm-based electronics in each joint provided the necessary controllability. The addition of increased self checks also assured better control of hardware failures that could cause hazardous on-orbit conditions.

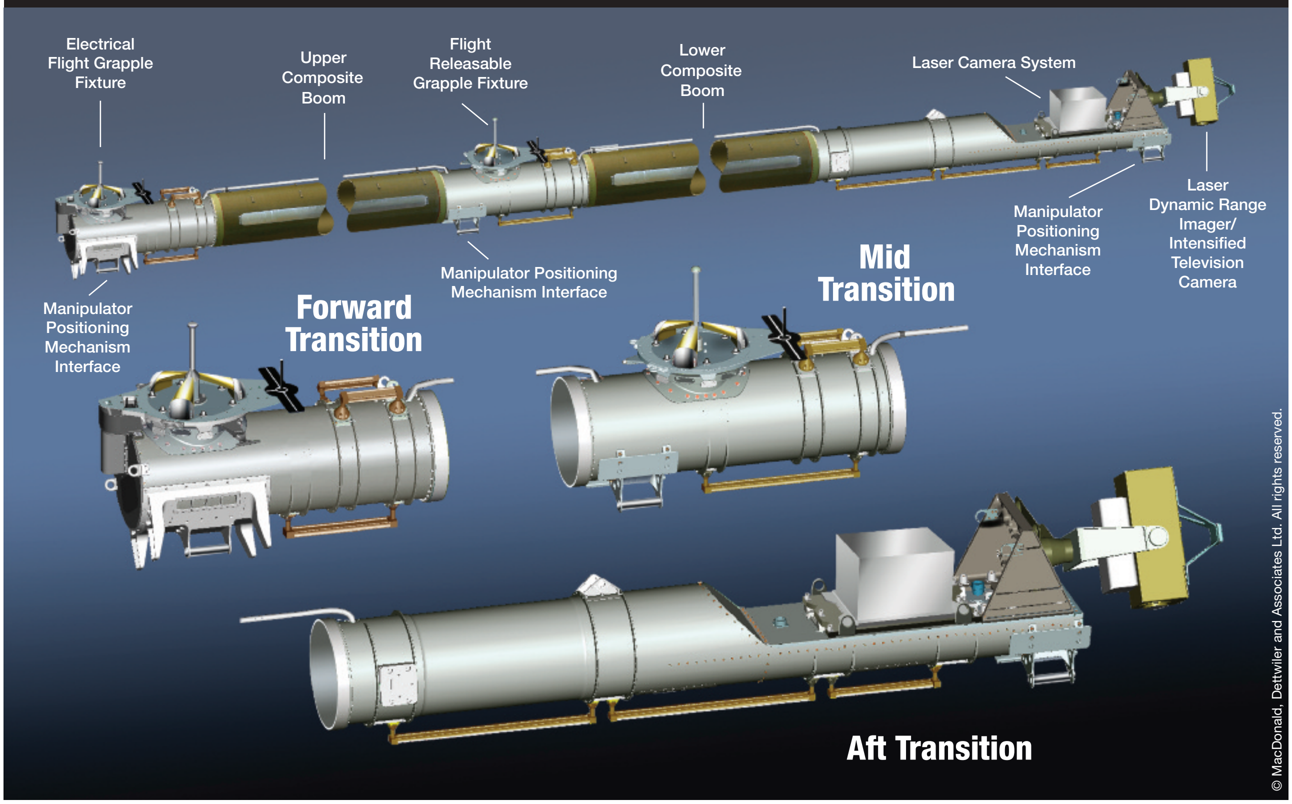
During the process of assembling the space station, enhanced berthing cue systems were necessary to mate complicated interfaces that would need to transmit loads and maintain a pressurized interior. The complexity and close tolerance of mating parts led to the development of several berthing cue systems, such as the Space Vision System and the Centerline Berthing Camera System, to enhance the crew's ability to determine relative position between mating modules.

Return to Flight After Columbia Accident

During the launch of STS-107 (2003), a piece of debris hit the shuttle, causing a rupture in the Thermal Protection System that is necessary for re-entry into Earth's atmosphere, thereby leading to the Columbia accident. The ramifications of this breach in the shuttle's Thermal Protection System changed the role of the robotic arm substantially for all post-Columbia-accident missions. Development of the robotically compatible 15.24-m (50-ft) Orbiter Boom Sensor System provided a shuttle inspection and repair capability that addressed the Thermal Protection System inspection requirement for post-Columbia Return to Flight missions. Modification of the robotic arm wiring provided power and data capabilities to support inspection cameras and lasers at the tip of the inspection boom.

Two shuttle repair capabilities were provided in support of the Return to Flight effort. The first repair scenario required the Shuttle Robotic Arm, grappled to the space station, to position the shuttle and the space station in a configuration that would enable a crew member on the Space Station Robotic Arm to perform a repair. This was referred to as the Orbiter repair maneuver. The second repair scenario involved the Shuttle Robotic Arm holding the boom with the astronaut at the tip.

Orbiter Boom Sensor System



The operational scenario was that, post ascent and pre re-entry into Earth's atmosphere, the robotic arm would reach over to the starboard side and grapple the Orbiter Boom Sensor System at the forward grapple fixture and unberth it. The robotic arm and boom would then be used to pose the inspection sensors at predetermined locations for a complete inspection of all critical Thermal Protection System surfaces. This task was broken up into phases: inspect the starboard side, the nose, the crew cabin, and the port side. When the scan was complete, the robotic arm would berth the Orbiter Boom Sensor System back on the starboard sill of the shuttle and continue with mission objectives.

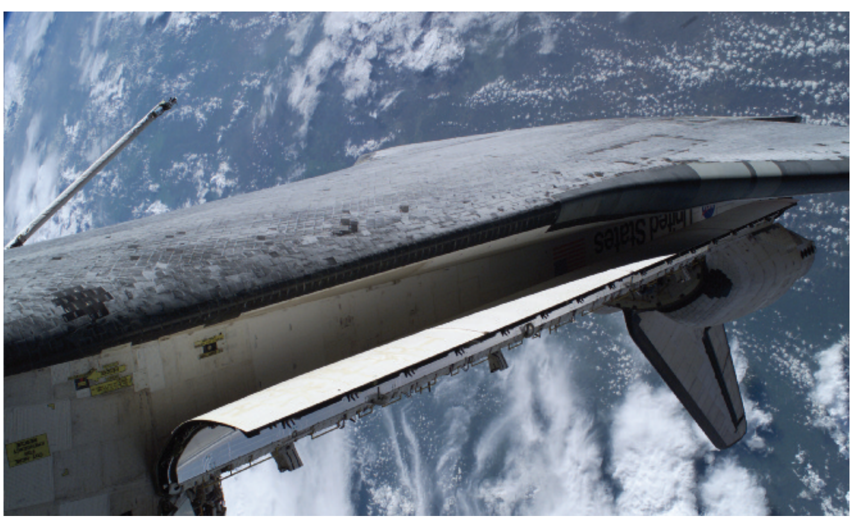
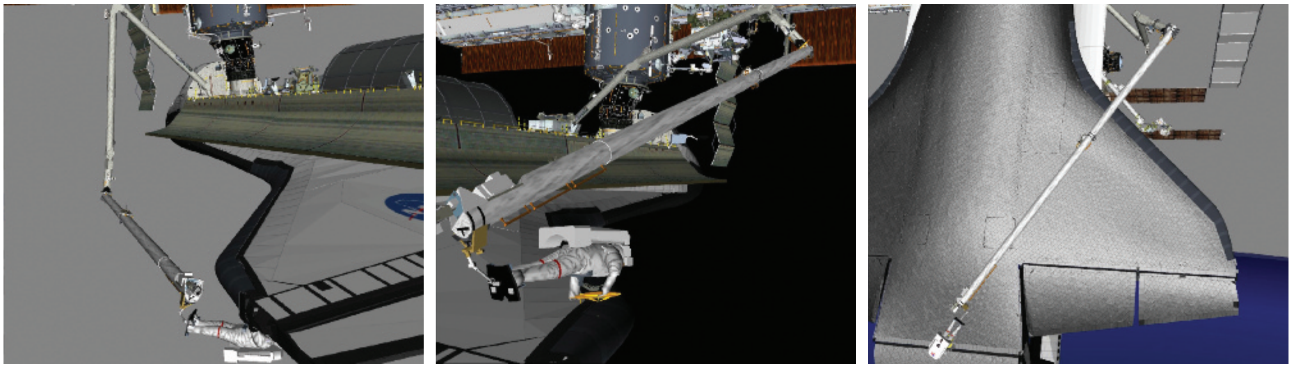
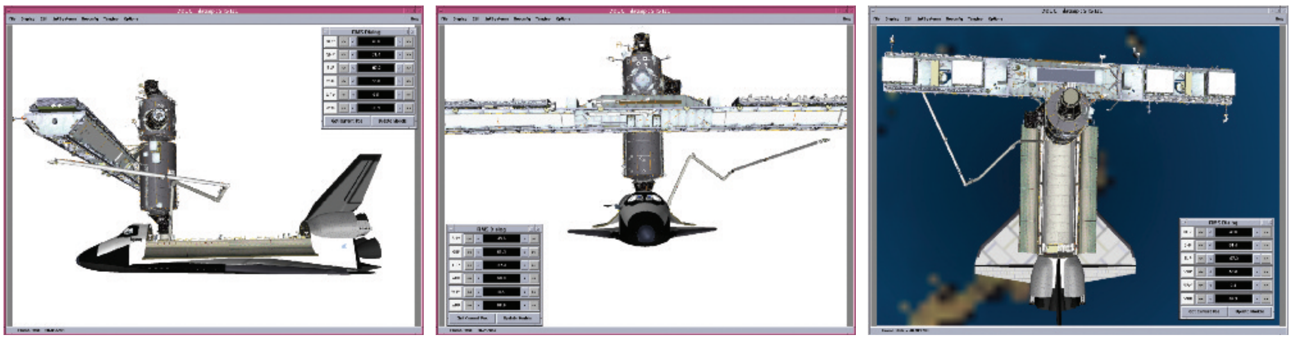


Image from STS-114 (2005) of the Orbiter Boom Sensor System scanning the Orbiter.

All post-Columbia-accident missions employed the Shuttle Robotic Arm and Orbiter Boom Sensor System combination to survey the shuttle for damage. The robotic arm and boom were used to inspect all critical Thermal Protection System surfaces. After the imagery data were processed, focused inspections occasionally followed to obtain additional images of areas deemed questionable from the inspection. A detailed test objective on STS-121 (2006) demonstrated the feasibility of having a crew member



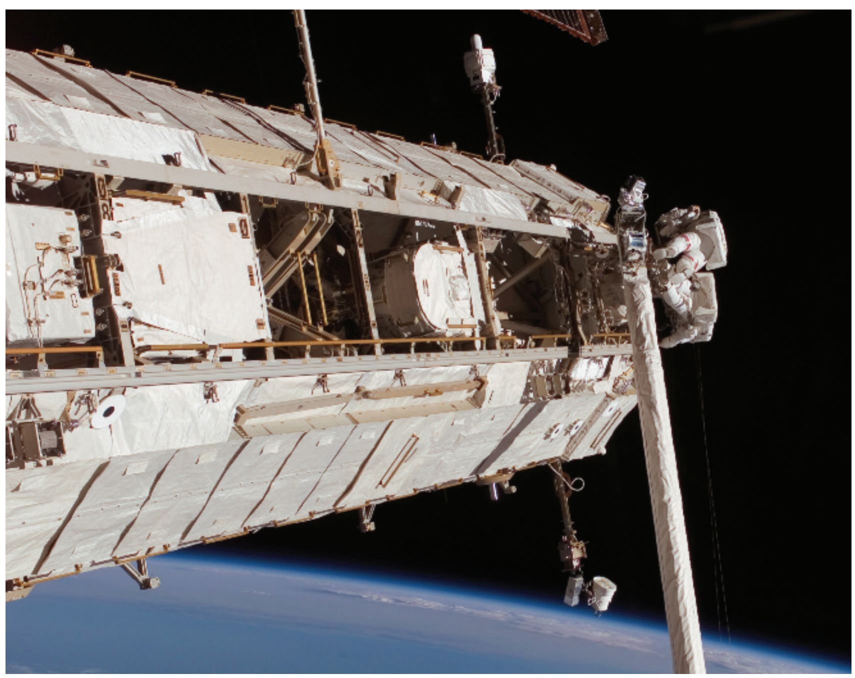
Graphic simulation of Shuttle Robotic Arm/Orbiter Boom Sensor System-based repair scenario for port wing tip, starboard wing, and Orbiter aft locations.



Graphic simulation of the configuration of the Shuttle Robotic Arm/Orbiter Boom Sensor System for STS-121 (2006) flight test.

on the end of the combined system performing actions similar to those necessary for Thermal Protection System repair. Test results showed that the integrated system could be used as a repair platform and the system was controllable with the correct control parameters, good crew training, and proper extravehicular activity procedures development.

In support of shuttle repair capability and rescue of the crew, simulation tools were updated to facilitate the handling of both the space station and another shuttle as "payloads." The space station as a payload was discussed earlier as a Return to Flight capability, known as the Orbiter repair maneuver. The shuttle as a payload came about due to the potential for a



In addition to performing inspections, the Orbiter Boom Sensor System's role was expanded to include the ability to hold a crew in position for a repair to the Thermal Protection System. Considering that this was a 30.48-m (100-ft) robotic system, there was concern over the dynamic behavior of this integrated system. The agency decided to perform a test to evaluate the stability and strength of the system during STS-121 (2006).

Hubble rescue mission. Given that the space station would not be available for crew rescue for the final Hubble servicing mission, another shuttle would be "ready to go" on another launch pad in the event the first shuttle became disabled. For the crew from the disabled shuttle to get to the rescue shuttle, the Shuttle Robotic Arm would act as an emergency pole between the two vehicles, thus making the payload for the Shuttle Robotic Arm another shuttle. Neither of these repair/rescue capabilities—Orbiter repair maneuver or Hubble rescue—ever had to be used.

Summary

The evolution of the Shuttle Robotic Arm represents one of the great legacies of the shuttle, and it provided the impetus and foundation for the Space Station Robotic Arm. From the early days of payload deployment and retrieval, to the development of berthing aids and techniques, to the ability to inspect the shuttle for damage and perform any necessary repairs, the journey has been remarkable and will serve as a blueprint for space robotics in the future.

Automation: The Space Shuttle Launch Processing System

The Launch Processing System supported the Space Shuttle Program for over 30 years evolving and adapting to changing requirements and technology and overcoming obsolescence challenges.

Designed and developed in the early 1970s, the Launch Processing System began operations in September 1977 with a focused emphasis on safety, operational resiliency, modularity, and flexibility. Over the years, the system expanded to include several firing rooms and smaller, specialized satellite sets to meet the processing needs of multiple Space Shuttles—from landing to launch.

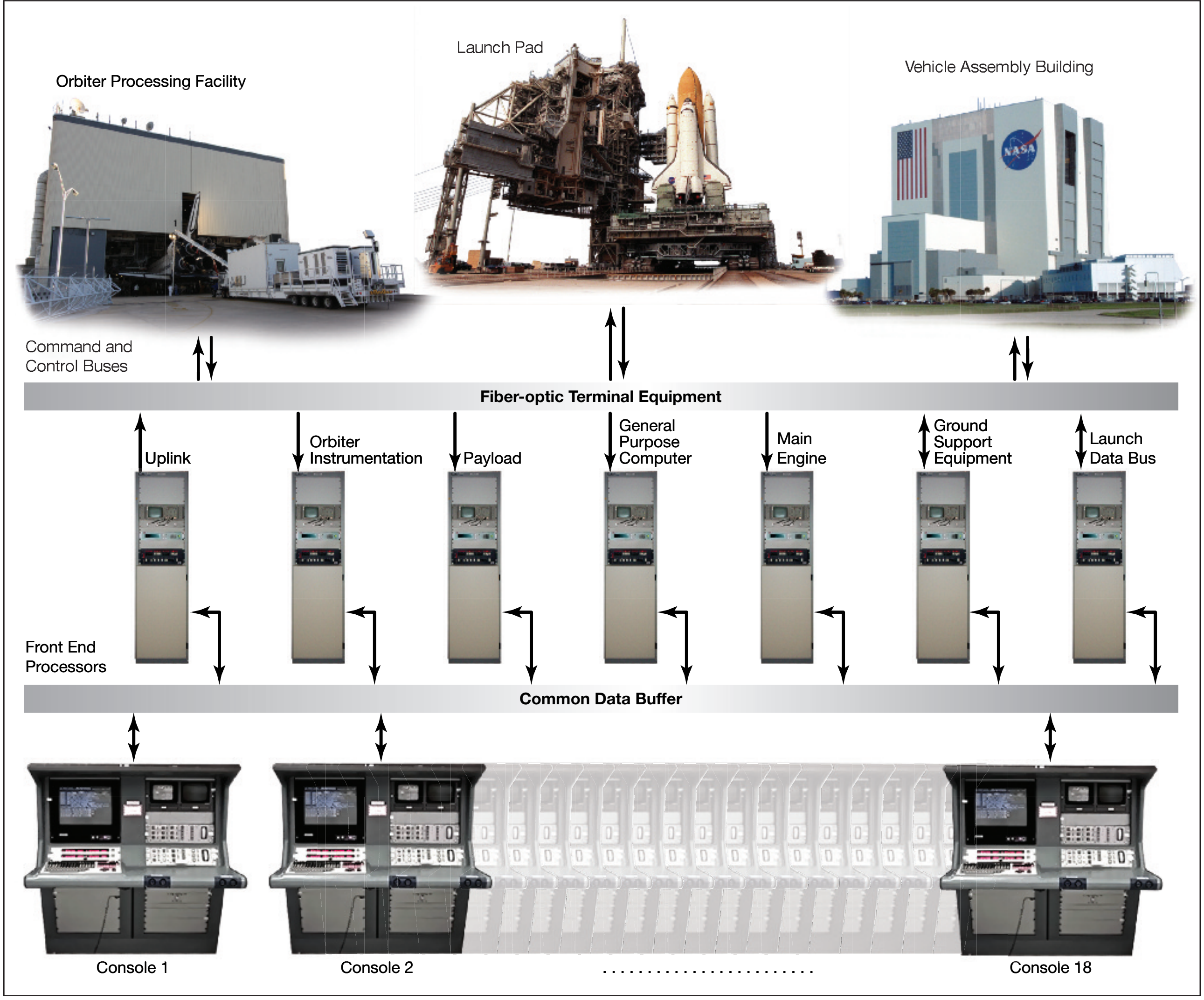
Architecture and Innovations

The architecture of the system and innovations included in the original design were major reasons for the Launch Processing System's outstanding success. The system design required that numerous computers had the capability to share real-time measurement and status data with each other about the shuttle, ground support equipment, and the health and status of the Launch Processing System itself. There were no commercially available products to support the large-scale distributed computer network required for the system. The solution to this problem was to network the Space Shuttle firing room computers using a centralized hub of memory called a common data buffer—designed by NASA at Kennedy Space Center (KSC) specifically for computer-to-computer communication. The buffer was a high-speed memory device that provided shared memory used by all command and control computers supporting a test. Each computer using the buffer was assigned a unique area of memory where only that computer could write data; however, every computer on the buffer could read those data. The buffer could support as many as 64 computers simultaneously and was designed with multiple layers of internal redundancy, including error-correcting software. The common data buffer's capability to provide fast and reliable intercomputer communication made it the foundation of the command and control capability of the firing room.

The System Console

Other outstanding features of the Launch Processing System resided in the human-to-machine interface known as the console. System engineers used the console to control and monitor the particular system for which they were responsible. Each firing room contained 18 consoles—each connected to the common data buffer, and each supporting three separate command and control workstations. One of the key features of the console was its ability to execute up to six application software programs, simultaneously. Each console had six "concurrencies"—or areas in console memory—that could independently support an application program. This capability foreshadowed the personal computer with its ability to multitask using different windows. With six concurrencies available to execute as many as six application programs, the console operator could monitor

Launch Processing System



The Launch Processing System provides command and control of the flight vehicle elements and ground support equipment during operations at Kennedy Space Center.

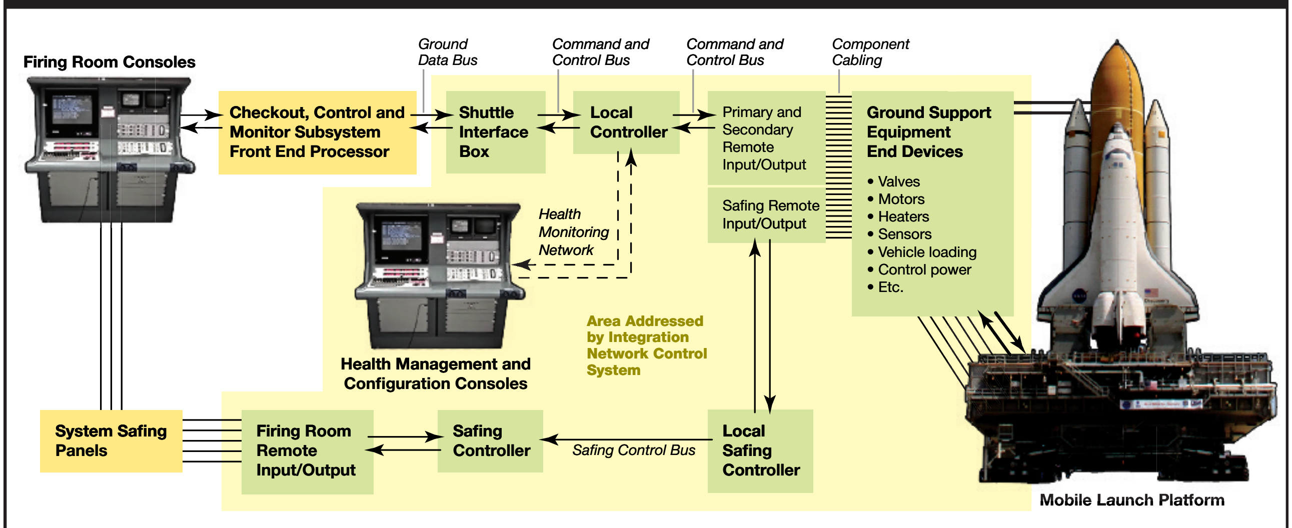
thousands of pieces of information within his or her area of responsibility from a single location. Each console in the firing room was functionally identical, and each was capable of executing any set of application software programs. This meant any console could be assigned to support any system, defined simply by what software was loaded. This flexibility allowed for several on-demand spare consoles for critical or hazardous tests such as launch countdown. The console also featured full color displays, programmable function keys, a programmable function panel, full cursor control, and a print screen capability. Upgrades included a mouse, which was added to the console, and modernized cursor control and selection.

System Integrity

Fault tolerance, or the ability to both automatically and manually recover from a hardware or software failure, was designed and built into the Launch Processing System. An equivalent analogy for distributed computer systems would be the clustering of servers for redundancy. Most critical computers within the system were operated in an active/standby configuration. A very high degree of system reliability was achieved through automated redundancy of critical components.

A software program called System Integrity, which constantly monitored the health and status of all computers using the common data buffer,

Integrated Network Control System



The Integrated Network Control System was a reliable, automated network system that sent data and commands between the shuttle Launch Control Center and hardware end items. It bridged industry automation technologies with customized aerospace industry communication protocols and associated legacy end item equipment. The design met several challenges, including connectivity with 40,000 end items located within 28 separate ground systems, all dispersed to 10 facilities. It provided data reliability, integrity, and emergency safing systems to ensure safe, successful launch operations.

Ground control and instrumentation systems for the Space Shuttle Launch Processing System used custom digital-to-analog hardware and software connected to an analog wire-based distribution system. Loss of a data path during critical operations would compromise safety. To improve safety, data integrity, and network connectivity, the Integrated Network Control System design used three independent networks.

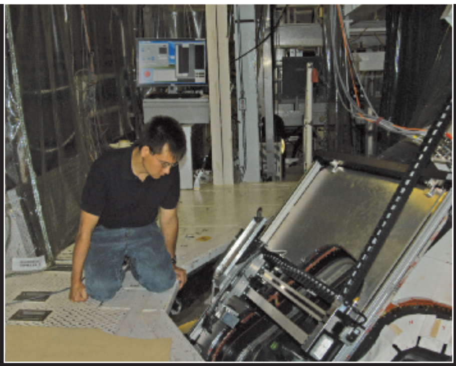
The network topology used a quad-redundant, fiber-optic, fault-tolerant ring for long-distance distribution over the Launch Control Center, mobile launcher platforms, Orbiter processing facilities, and two launch pads. Shorter distances were accommodated with redundant media over coaxial cable for distribution over system and subsystem levels. This network reduced cable and wiring for ground processing over the Launch Complex 39 area by approximately 80% and cable interconnects by 75%. It also reduced maintenance and troubleshooting. This system was the first large-scale network control and health management system for the Space Shuttle Program and one of the largest, fully integrated control networks in the world.

governed the automatic recovery of failed critical computers in the firing room. In the event of a critical computer failure, System Integrity commanded a redundant switch, thereby shutting down the unhealthy computer and commanding the standby computer to take its place. Launch Processing System operators could then bring another standby computer on line from a pool of ready spares to reestablish the active/standby configuration.

Most critical portions of the Launch Processing System had redundancy and/or on-demand spare capabilities. Critical data communication buses between the Launch Control Center and the different areas where the shuttles were processed used both primary and backup buses. Critical ground support equipment measurements were provided with a level of redundancy, with a backup measurement residing on a fully independent circuit and processed by different firing room computers than the primary measurement. Electrical power to the firing room was supplied by dual uninterruptible power sources, enabling all critical systems to take advantage of two sources of uninterruptible power.

Critical software programs, such as those executed during launch countdown, were often part of the software load of two different consoles in the event of a console failure. The System Integrity program was executed simultaneously on two different firing room consoles. The fault tolerance designed into the Launch Processing System spanned from the individual measurement up through subsystem hardware and software, providing the Space Shuttle test team with outstanding operational resiliency in almost any failure scenario.

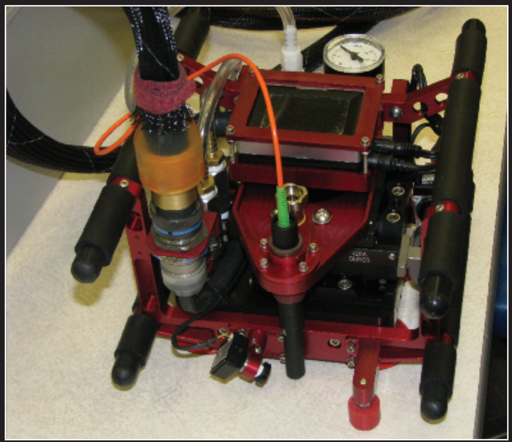
Orbiter Window Inspection



Bradley Burns, lead engineer in the development of the window inspection tool, monitors its progress as it scans an Orbiter window.

As the Orbiter moved through low-Earth orbit, micrometeors collided with it and produced hypervelocity impact craters that could produce weak points in its windows and cause the windows to fail during extreme conditions. Consequently, locating and evaluating these craters, as well as other damage, was critically important. Significant effort went into the development and use of ground window inspection techniques.

The window inspection tool could be directly attached to any of the six forward windows on any Orbiter. The tool consisted of a dual-camera system—a folded microscope and a direct stress imaging camera that was scanned over the entire area of the window. The stress imaging camera “saw” stress by launching polarized light at the window from an angle such that it bounced off the back of the window, then through the area being monitored, and finally into the camera where the polarization state was measured. Defects caused stress in the window. The stress changed the polarization of the light passing through it. The camera provided direct imaging of stress regions and, when coupled with the microscope, ensured the detection of significant defects.



The Portable Handheld Optical Window Inspection Device is vacuum attached to a window such that the small camera and optical sensor (black tube) were aimed at a defect.

The portable defect inspection device used an optical sensor. A three-dimensional topographic map of the defect could be obtained through scanning. Once a defect was found, the launch commit criteria was based on measuring the depth of that defect. If a window had a single defect deeper than a critical value, the window had to be replaced.

Robotics System Sprayed Thermal Protection on Solid Rocket Booster

Many Solid Rocket Booster (SRB) components were covered with a spray-on thermal protection material that shielded components from aerodynamic heating during ascent. The application process took place at the SRB Assembly and Refurbishment Facility at Kennedy Space Center. The process resulted in overspray and accounted for 27% of hazardous air emissions.

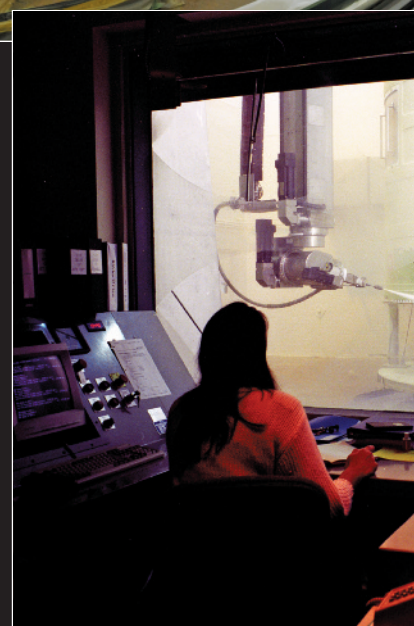
An SRB aft skirt receives a robotically controlled layer of Marshall Convergent Coating-1 Thermal Protection System material.

To address this drawback, NASA developed Marshall Convergent Coating-I, which consisted of improved mixing and robotic spray processes. The coating's ingredients were mixed (or *converged*) only during spraying. Hazardous waste was virtually eliminated after implementation of the system in the mid 1990s.

After each flight, the boosters were refurbished. This process began at NASA's Hangar AF Booster Recovery Facility at Cape Canaveral Air Force Station. There, a robotic high-pressure water jet, or "hydrolase," stripped the components of their Thermal Protection System materials.

NASA installed the hydrolase system in 1998. Each booster structure was numerically modeled. These models were used to program the robot to follow the contour of each component.

The Hangar AF wash facilities used a specially designed water filtration and circulation system to recycle and reuse the waste water.



A technician in a control booth monitors the robotic high-pressure hydrolase as it strips Thermal Protection System material from an SRB forward skirt.

Exception Monitoring

Another key concept designed into the Launch Processing System software was the capability to recognize and automatically react to out-of-bounds measurements. This capability was called exception monitoring, and it monitored for specific measurements exceeding a predefined set of limits. When a Launch Processing System computer detected a measurement exception—for example, the pressure in a fuel tank exceeded its upper limit—the computer immediately notified the console responsible for that fuel tank. A software program at the console promptly reacted to the exception and automatically sent a command or series of commands to resolve the problem. Similar software could also prevent inadvertent damage by verifying required parameters prior to command issuance, such as confirming that pressures were appropriate prior to commanding a valve opening. Commands could also be manually sent by the console operator.

Survivability

Although the Launch Processing System's flexible architecture and distribution of hardware functionality allowed it to support the program consistently over 30 years, that support would not have been possible without a comprehensive and proactive sustaining engineering, maintenance, and upgrade approach. This is true for any large-scale computer system where an extended operational lifetime is desired.

The approach that kept the Launch Processing System operationally viable for over 3 decades was called the Survivability Program. Survivability was initiated to mitigate risk associated with the natural obsolescence of commercial off-the-shelf hardware products and the physical wear and tear on the electrical and mechanical subsystems within the Launch Processing System.

One of the main tenets of survivability was the desire to perform each upgrade with an absolutely minimal impact to system software. Hardware was upgraded to duplicate the existing hardware in form, fit, and function. The emphasis on minimizing software impacts was a distinct strength in survivability due to the resultant reduction of risk. Survivability projects were selected through careful analysis of maintenance failure data and constant surveillance of electronic manufacturers and suppliers by logistics to identify integrated circuits and other key components that were going to be unavailable in the near future. Through this process, NASA purchased a "lifetime" buy of some electronic components and integrated circuits to ensure the Launch Processing System had ample spares for repair until the end of the program. It could also redesign a circuit board using available parts or replace an entire subsystem if a commercial off-the-shelf or in-house design solution offered the most benefit.

NASA eventually upgraded or replaced about 70% of the original Launch Processing System hardware under the survivability effort. The proactive application of the Survivability Program mitigated obsolescence and continued successful operational support.

Summary

These innovations and the distributed architecture of the Launch Processing System allowed upgrades to be performed over the years to ensure the system would survive through the life of the program. This success demonstrated that, with appropriate attention paid to architecture and system design and with proactive sustaining engineering and maintenance efforts, a large, modular, integrated system of computers could withstand the inevitable requirements change and obsolescence issues. It also demonstrated that it could successfully serve a program much longer than originally envisioned.

The Launch Processing System was vital to the success of KSC fulfilling its primary mission of flying out the Space Shuttle Program in a safe and reliable manner, thus contributing to the shuttle's overall legacy.